introduction to...

KLYSTRON AMPLIFIERS

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introduction to

Klystron Amplifiers

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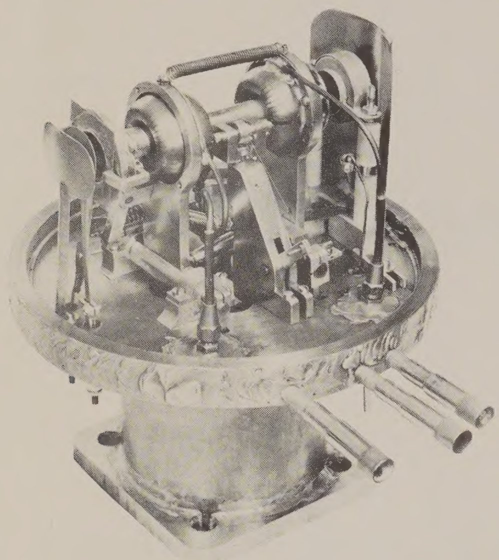
This discussion is primarily for those engineers and technicians with little or no knowledge of microwaves who may find themselves suddenly confronted with operating and maintaining a high power microwave transmitter using klystron amplifier tubes. It is assumed that the reader is familiar with the theory and operation of triode rf amplifiers and general electronic circuit theory. We will discuss a simplified theory of operation for klystron amplifier tubes, the associated equipment which is required to make a klystron amplifier tube operate properly, some of the things which must be protected from malfunction, and some generalized operating procedures associated with this type of equipment. After reading this information the reader will not be able to design a klystron amplifier; however, he should be in a position to better understand what is going on in the equipment and the reasons behind some of the operating instructions which are presented in a typical klystron amplifier Instruction Manual. Knowing and understanding this simple theory should help the operator to realize "why" certain functions are built into a klystron amplifier, and the "why" of certain operating instructions which he may receive. We feel that this understanding is important to a man who must operate or service a fairly complicated and expensive piece of electronic equipment.

A little history: The klystron amplifier was in its infancy even at the end of World War II, although reflex klystrons had been developed (for use as local oscillators in radar receivers) to a fairly high degree of sophistication by the end of the war. Since World War II the klystron amplifier has undergone a spectacular evolution. It has become one of the most-widely used devices for the amplification of microwave signals, particularly for high power applications. Klystron amplifiers currently in production cover microwave frequency ranges from UHF to 100 Gc, or higher; outputs range from a few milliwatts to many megawatts peak and over 100 kilowatts average; power gains vary from 3 to 90 db; and sizes vary from extremely small tubes which can be held easily in the palm of the hand to tubes which are more than 12 feet long. The uses of klystron amplifiers cover almost every microwave application, from low level signal generators, to giant radar equipment and huge transmitters

for deep space communication and command. Some of the equipment is complicated and quite expensive. A serious shortage of engineers and technicians trained to operate and maintain this equipment has resulted from the rapidity with which this equipment has been developed and produced. Many engineers and technicians, experienced on lower frequency equipment using conventional vacuum tubes, have required re-training to operate this microwave equipment. We hope this information will help slightly in the training process.



This two-cavity oscillator, built in 1937 by the Varian brothers, was one of the first tubes to demonstrate the principle of the klystron successfully. The tube operated at about 10 centimeters; the entire assembly was arranged for operation within a vacuum bell jar to simplify experimental modifications and adjustments.

THEORY OF KLYSTRON OPERATION

The basic theory of klystron amplification is quite simple. In fact, the klystron amplification principle can be readily explained by an analogy with a simple triode rf amplifier. Obviously there are some differences (which will be explained), and these differences are what make a klystron amplify at microwave frequencies whereas a triode will not. First, let us consider the basic theory of operation of a simple triode amplifier.

Figure 1 shows a simplified diagram of a triode amplifier with resonant circuits at both the input and the output. Such resonant circuits restrict the bandwidth of the amplifier and increase the gain. Such an amplifier might be part of an intermediate frequency amplifier circuit typically used at frequencies from 10 to 100 megacycles. A triode radio tube consists of three elements: a cathode which emits a stream of electrons, a grid that stands in the path of the stream, and a plate that attracts the electrons and catches them after they pass through the grid. The grid acts as a valve, opening or closing the passage of electrons according to the voltage on it. The rf input signal comes to the grid as a weak alternating current, oscillating at the rf frequency. The oscillating voltage thus applied to the grid modulates the flow of electrons across the tube at the rf frequency. The electron stream then delivers, at the plate, an alternating current which reproduces the weak signal on the grid with amplification. This alternating current at the plate flows through the resonant plate circuit and excites alternating voltages across it; these voltages constitute the rf output from the amplifier.

Now the time it takes an electron to cross the tube is in the order of a billionth of a second. This transit time is short compared to the cycle of a long radio wave (around a millionth of a second); hence the electron is slowed or speeded by the voltage on the grid at a given moment of the rf cycle. The flow of electrons, therefore, can "follow" the voltage fluctuations on the grid. In the case of microwaves, however, the oscillations are so rapid (i.e., the cycle is so short) that the volt-

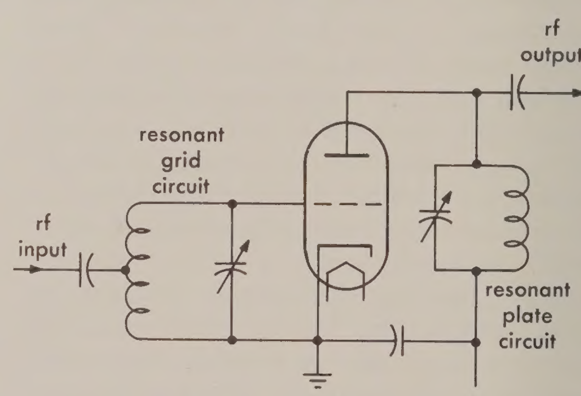


Figure 1. Triode vacuum tube RF amplifier

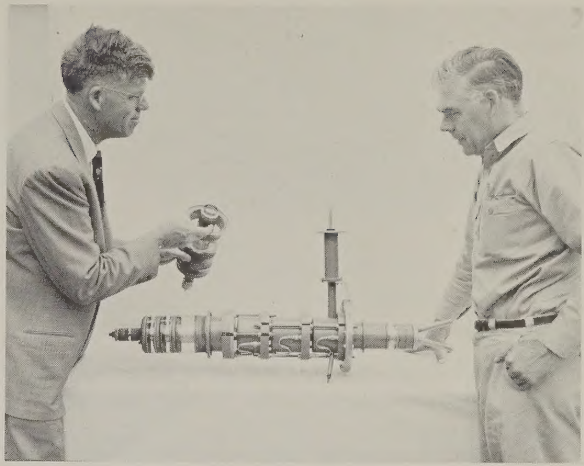
age on the grid may go through several complete oscillations while an electron travels across the tube. In other words, the grid voltage changes too fast and produces only chaos among the electrons. The grid voltage can no longer impose its signal pattern on the electron flow. There are other reasons why the conventional triode tube fails in the micro-

wave range, but this is the most fundamental one—the simple fact that the transit time of an electron from cathode to plate is long compared to the time of one cycle of the microwave signal.

The klystron tube makes a virtue of the very thing that defeats the triode—the transit time of the electrons. What it does is to "modulate" the velocity of electrons so that, as they travel through the tube, they sort themselves into groups and arrive at their destination in bunches. These bunches deliver an oscillating current to the output resonant circuit of the klystron.

Figure 2 shows a cutaway representation of a typical klystron amplifier. Schematically it is very similar to a triode amplifier in that it includes an electron gun, resonant circuits, and a collector (which is roughly equivalent to the plate of a triode). In fact, the klystron amplifier consists of three separate sections—the electron gun, the rf section and the collector section.

Let us consider, first, the electron gun structure: As in the triode, the electron gun consists of heater and cathode, a control grid (sometimes), and an anode. Electrons are emitted by the hot cathode surface and are drawn toward the anode which is operated at a positive potential with respect to the cathode. The electrons are formed into a small, dense beam by either electrostatic or magnetic focusing techniques, similar to the techniques used for beam formation in a cathode ray tube. In some klystron amplifiers a control grid is used to permit adjustment of the number of electrons which reach the anode region; this control grid may be used to turn the tube completely on or completely off in certain pulsed-amplifier applications. The electron beam is well formed by the time it reaches the anode. It passes through a hole in the anode, passes on to the rf section of the tube, and eventually the electrons are intercepted by the collector. The electrons are returned to the cathode through an external power supply (not shown on Figure 2). It is evident that the collector in the klystron acts much like the plate of a triode insofar as collecting of the electrons is concerned. However, there is one important difference; the plate of a triode is normally connected in some fashion to the output rf circuit, whereas, in a klystron amplifier, the collector has no connection to the rf circuitry at all. From the above discussion it is apparent that the klystron



Russel and Sigurd Varian are shown discussing an early high-power klystron. This tube was built by Varian Associates for the National Bureau of Standards to study microwave propagation in 1951. Transmitting 5 kilowatts CW on 1050 Mc from Cheyenne Mountain, Colorado, this tube established the feasibility of long-distance microwave communication.

amplifier, insofar as the electron flow is concerned, is quite analogous to a "stretched-out" triode tube in that electrons are emitted by the cathode, controlled in number by the control grid, and collected eventually by the collector.

Now let us consider the rf section of a klystron amplifier. This part of the tube is physically quite different from a triode amplifier. One of the major differences is in the physical configuration of the resonant circuit used in a klystron amplifier. The resonant circuit used with a triode oscillator, at lower frequencies, is generally composed of an inductance and a capacitor, while the resonant circuit used in a microwave tube is almost invariably a metal-enclosed chamber, known as a cavity resonator. A very crude analogy can be made between the resonant cavity and a conventional L-C resonant circuit. The gap in the cavity (see Figure 2) is roughly analogous to the capacitor in a conventional low frequency resonant circuit in that alternating voltages, at the rf frequencies, can be made to appear across the cavity gap. Circulating currents will flow between the two sides of the gap through the metal walls of the cavity, roughly analogous to the flow of rf current in the inductance of an L-C resonant circuit. Since rf voltages appear across the sides of the cavity gap it is apparent that an electric field will be present, oscillating at the rf frequency, between the two surfaces of the cavity gap.

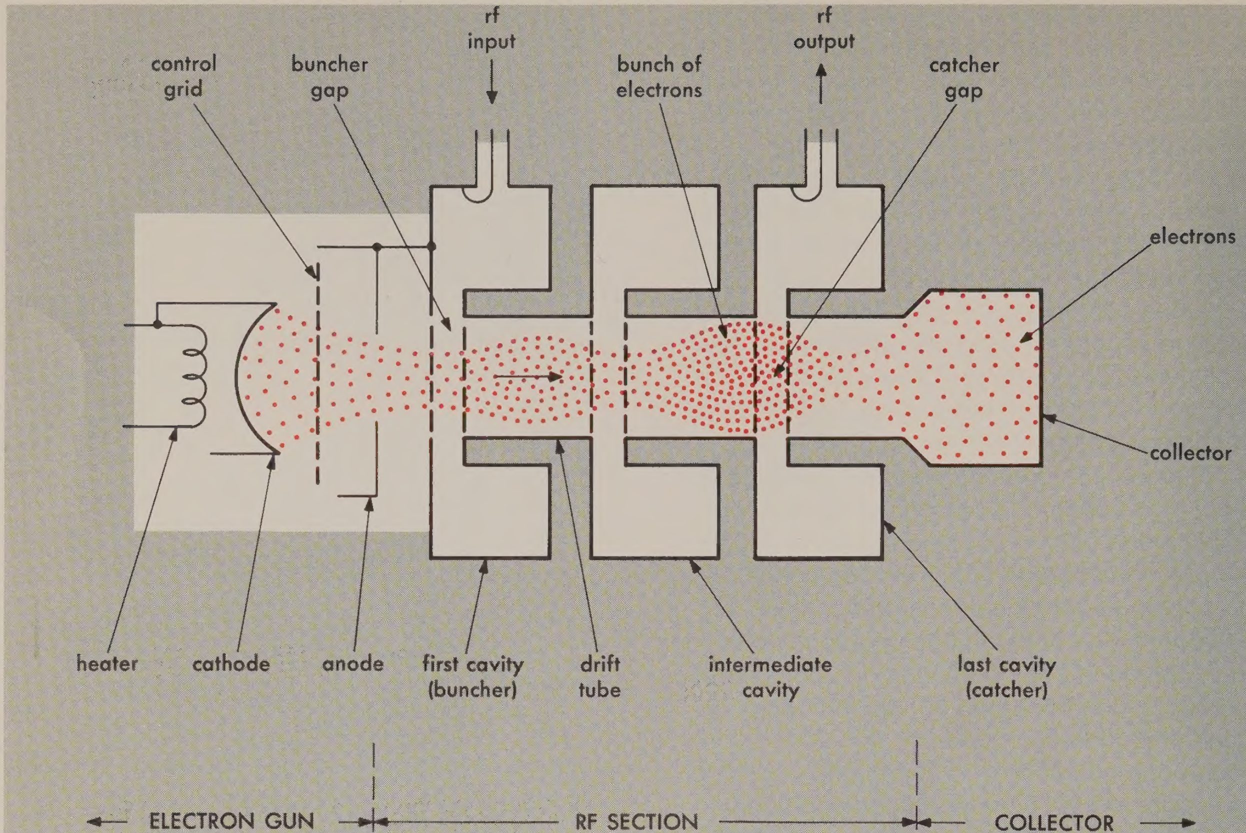


Figure 2. Sectional view of a klystron

When a cavity is the correct size it will resonate to microwaves of a certain frequency. The cavity can be tuned to various microwave frequencies by adjusting its size by some mechanical means. A crude analogy to the cavity resonator would be a glass goblet which resonates at a certain pitch depending on the level of the water in it—i.e., the size of the air cavity in the goblet.

As shown in Figure 2, electrons pass through the cavity gaps in each of the resonators, and pass through cylindrical metal tubes between the various gaps. These metal tubes are called "drift tubes." In a klystron amplifier the low-level rf input signal is coupled to the first resonator, which is called the "buncher" cavity. The signal may be coupled in through either a waveguide or a coaxial connection. The rf input signal will excite oscillating currents in the cavity walls, if the cavity is the correct size (that is, tuned to the right frequency). These oscillating currents will cause the alternate sides of the buncher gap to become first positive, and then negative, in potential at a frequency equal to the frequency of the rf input signal. Therefore, an electric field will appear across the buncher gap, alternating at the rf frequency. This electric field will, for half a cycle, be in a direction which will tend to speed up the electrons flowing through the gap; on the other half of the cycle the electric field will be in a direction which will tend to slow down the electrons as they cross the buncher gap. This effect is called "velocity modulation," and it is the mechanism which permits the klystron amplifier to operate at frequencies higher than the triode.

After leaving the buncher gap the electrons proceed toward the collector in the drift tube region. Ignore for the moment the intermediate resonator shown in Figure 2, and let us consider the simple case of a two-cavity klystron amplifier. In the drift tube region the electrons which have been speeded up by the electric field in the buncher gap will tend to overtake those electrons which have previously been slowed down (by the preceding half of the rf wave across the buncher gap). It is apparent that, since some electrons are tending to overtake other electrons, clumps or "bunches" of electrons will be formed in the drift tube region. If the average velocity of the electron stream is correct, as determined

by the original voltage between anode and cathode, and if the length of the drift tube is proper, these "bunches" of electrons will be quite completely formed by the time they reach the catcher gap of the last cavity (which is called the "catcher"). This results in bunches of electrons flowing through the catcher gap periodically, and during the time between these bunches relatively fewer electrons flow through the catcher gap. The time between arrival of bunches of electrons is equal to the time of one cycle of the rf input signal.

These bunches of electrons will induce alternating current flow in the metal walls of the catcher cavity as they pass through the catcher gap. If the catcher cavity is of correct size (tuned to the proper frequency) large oscillating currents will be generated in its walls. These currents cause electric fields to exist, at the rf frequency, within the catcher cavity. These electric fields can be coupled from the cavity (to output waveguide or coaxial transmission lines) resulting in the rf output from the tube.

It is not particularly obvious why a bunch of electrons, passing through the catcher gap, should generate an oscillating rf current in the walls of the catcher cavity. Fortunately, a qualitative explanation is easy to understand. Refer to Figure 3 which shows the catcher cavity at three instants of time as a bunch of electrons flow across the catcher gap. The electrons are shown passing the catcher gap, traveling from left to right. To simplify the explanation, we have shown grid wires across the gaps; the grid on the left side of the gap is labeled No. 1, while the grid on the right is labeled No. 2. Since the grid wires, and the cavity walls, are made of high-conductivity metal, such as copper, a large number of free electrons will be present in the metal. In Figure 3, as the bunch of electrons approaches Grid No. 1 the free electrons in Grid No. 1 will be repelled—since negative charges repel each other. This will tend to cause these electrons to flow from the grid wires into the cavity walls and around the cavity walls toward Grid No. 2. This is shown by the current flow path in Figure 3a. The result is that Grid No. 2 will tend to accumulate a surplus of negative charges, whereas Grid No. 1 will have a scarcity of negative charges present. Figure 3b shows the instant when the bunch of electrons is between Grids 1 and 2. At this instant the electrons in the bunch are repelling free electrons in both grids equally, and the net current flow around the cavity walls is essentially zero. Figure 3c shows the instant just after the electron bunch has passed to the right of Grid No. 2. Remember that Grid No. 2 has accumulated an excess of free electrons already and these free electrons would tend to redistribute themselves back toward Grid No. 1 even if the electron bunch was not present. However, the electron bunch further repels the excess free electrons in Grid No. 2 and tends to "push" these free electrons back toward Grid No. 1. As the electron bunch moves further to the right the electrons will redistribute themselves to essentially an equilibrium con-

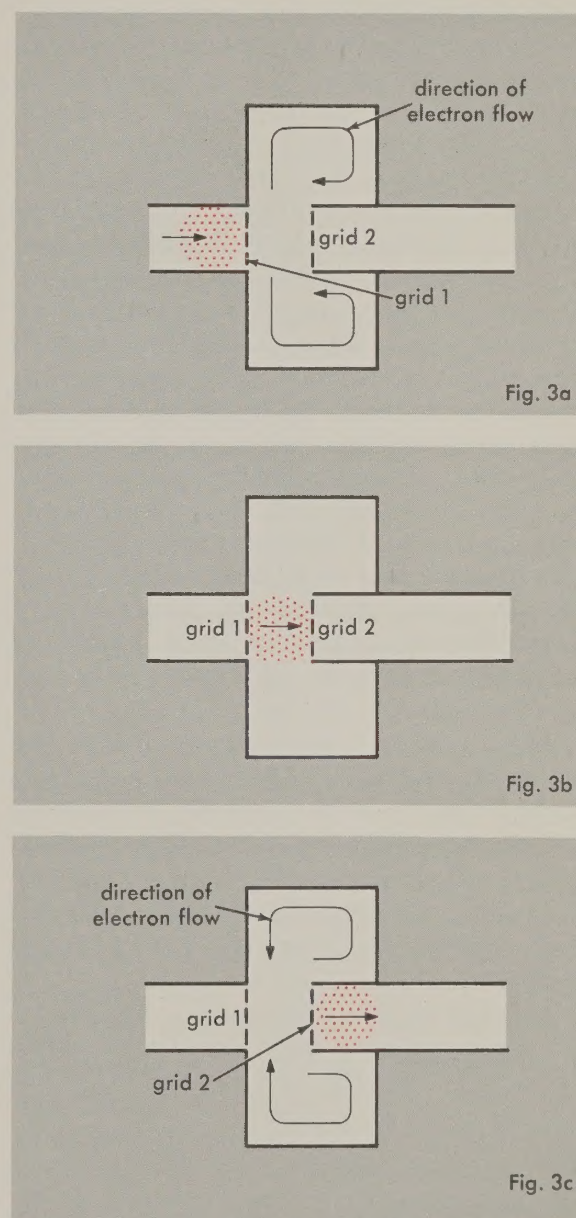


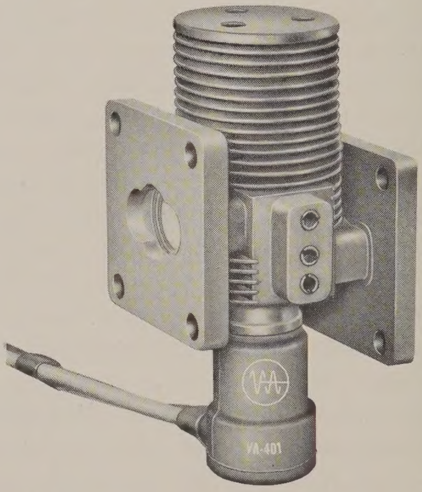
Figure 3. Generation of alternating current in a cavity

dition during the time "between bunches." The process of course repeats every cycle of the rf wave because a bunch of electrons comes past the catcher gap in a time equal to the time interval of one cycle of the rf wave. Since the resonant cavity is a high-Q circuit the oscillating currents tend to be essentially sinusoidal even though the bunches of electrons arrive in short bursts. The situation is quite analogous to striking a pendulum one blow for each cycle of its oscillation; this will cause the pendulum oscillation to build up even though the driving force is not continuously applied. Another analogy is a Class C triode amplifier where bursts of current generate essentially sinusoidal voltages in the plate resonant circuit.

RF power can be taken from the output (catcher) cavity by coupling to the oscillating current flowing in the cavity walls (or to the electric fields inside the cavity which are generated by these oscillating currents). If the amplifier is functioning properly the oscillating current in the catcher cavity will be considerably larger than the oscillating currents in the buncher cavity; consequently, amplification has taken place. When the bunches of electrons pass through the output gap in the catcher cavity they deliver energy to this cavity which causes currents to flow in the cavity walls. Since the electron beam is delivering energy to the cavity it is slowed up in velocity; therefore the beam arrives at the collector with less total energy than it had when it passed through the input cavity. This difference in electron beam energy is approximately equal to the rf energy delivered from the output of the cavity.

It is appropriate to mention here that the velocity modulation effect does not form "perfect" bunches of electrons. There are some electrons which come through "out-of-phase." These electrons show up at the last gap between the bunches. The electric field, at the time these out-of-phase electrons come through, is in a direction to accelerate them; so some few electrons will actually have their velocity increased as they come through the output gap. The electrons reaching the collector therefore have a wide spread of energy. Some of them (the out-of-phase electrons) may have velocities almost twice as high as the average electron velocity; other electrons (the "in-phase," useful electrons) will be materially slowed up and will arrive at the collector with a velocity much less than they started with.

In the previous discussion we have considered only a two-cavity klystron amplifier, having neglected the intermediate cavity shown on Figure 2. Klystron amplifiers have been built (to our knowledge) with as many as seven cavities—i.e., with five intermediate cavities. The effect of the intermediate cavities is to improve the bunching process; the result is to increase amplifier gain, and to a lesser extent, the amplifier efficiency. Adding more intermediate cavities is roughly analogous to adding more stages to an i-f amplifier —i.e., the gain of the overall amplifier is increased, and the overall bandwidth is reduced, if all stages are tuned to the same frequency. The same effect occurs with the klystron amplifier. However, it is well known that the bandwidth can be increased, and the gain reduced, by stagger-tuning an i-f amplifier. This analogy carries over to the klystron amplifier. A given klystron amplifier tube will deliver high gain and narrow bandwidth if all the cavities are tuned to the same frequency; this is called "synchronous-tuning." If the cavities are tuned to different frequencies the gain of the klystron amplifier will be reduced and the bandwidth may be appreciably increased; this is called "stagger-tuning." Almost all klystrons which feature relatively-wide bandwidths are stagger-tuned. The appropriate method of accomplishing stagger-tuning is discussed in more detail later.



Three-cavity air-cooled electrostatically-focussed klystron amplifier. This tube delivers 12 watts CW or 500-watt pulses. It can be furnished for any frequency from about 8 to 12 Gc and can be adjusted ±10 Mc by the user. Type of construction is well adapted to airborne applications including doppler navigators.

The klystron is not a "perfect" linear amplifier; that is, the rf power output is not linearly related to the rf power input at all operating levels. Another way of stating this is that the klystron amplifier will "saturate," just as a triode amplifier will "limit" if the input signal becomes too large. In fact, if the rf input is increased to levels above saturation, the rf power output will actually decrease. Figure 4 shows the plot of typical klystron amplifier performance for various tuning conditions. The rf output is plotted as a function of the rf input. Curve A of Figure 4 shows typical performance for synchronous tuning. Under these conditions the tube has maximum gain. The power output is almost perfectly linear, with respect to the power input, up to about 70 per cent of saturation. However, as the rf input is increased beyond that point, the gain decreases and the tube saturates. As the rf input is increased beyond saturation the rf output decreases. The reason for this decrease in output is quite interesting. Remember, in our previous discussion, that the electron bunches were formed by the action of the rf voltage across the buncher cavity gap. This rf voltage speeded up some electrons and slowed down other electrons, resulting in formation of bunches in the drift tube region. Obviously this speeding up and slowing down effect will be increased as the rf drive power is increased. The saturation point on Figure 4 is reached when the bunches are most perfectly formed at the instant they reach the output (catcher) gap. This results in the maximum power output condition. When the rf input is increased beyond this point, the bunches are most perfectly formed *before* they reach the output gap—i.e., they form too soon in the drift tube region. By the time the bunches have reached the output gap they tend to "debunch" because of the mutual repulsion of the electrons, and because the faster electrons have overtaken and passed the slower electrons. This causes the power output to decrease.

Curves B, C, and D illustrate a phenomenon of klystron amplifiers which is difficult to explain theoretically, but which should be recognized by personnel operating these amplifiers. It turns out that, if we start with a multi-cavity klystron which is synchronously tuned, and then tune the next-to-the-last cavity to a higher frequency, we find that the gain of the amplifier is reduced but that the saturation power output level may be increased. This effect is shown by curves B and C. Curve B represents a small amount of detuning of the next-to-the-last cavity, and curve C represents even more detuning of that cavity. Note that the gain of the tube has been reduced (it takes more rf input to obtain a given rf output), and that the saturation output power is higher than obtained with synchronous-tuning (curve A). As stated previously, this stagger-tuning also results in wider bandwidth for the amplifier. Many klystron amplifiers are operated in this fashion because it enables one to obtain more power output, with the same beam power input, and therefore increases the efficiency of the tube; of course this can only be done if enough rf drive power is available to operate under the stagger-tuned condition. As one might intuitively expect, we can go too far with this stagger-tuning, and the saturation output will eventually drop. This is illustrated by curve D of Figure 4.

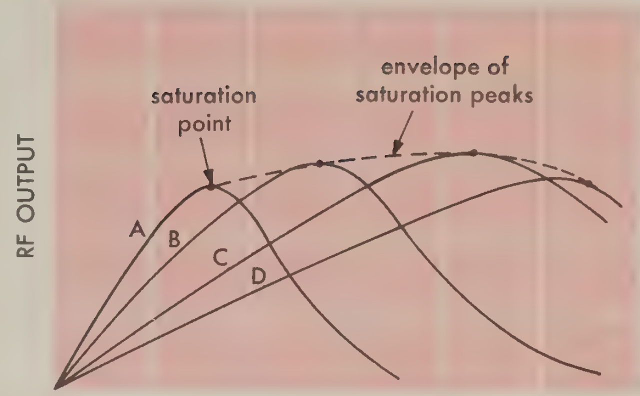
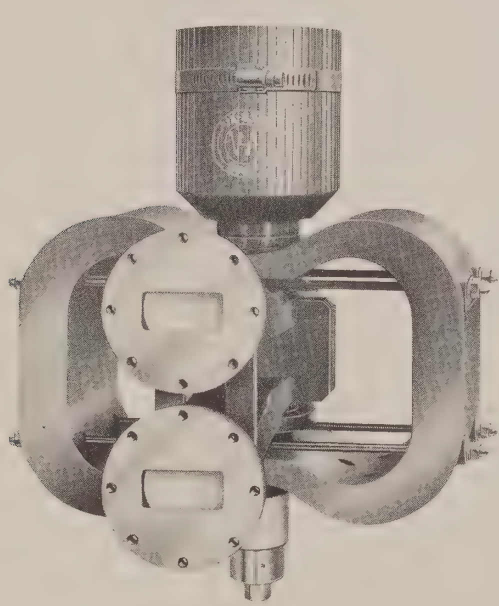


Figure 4. Effect of tuning on klystron performance

Figure 2 does not show one very important item which is usually required for high power klystron amplifier operation. This is an axial magnetic field—i.e., one which is parallel to the center line of the klystron. In klystron amplifiers which are physically "long" it is quite difficult to keep the electron beam formed properly during its travel through the rf section. Since electrons are negatively charged particles they tend to repel each other; this causes the beam to "spread" in a direction perpendicular to the axis of the tube. If this occurs the electrons will strike the drift tubes and be collected there, rather than passing through the drift tubes to the collector. To overcome this beam spreading an axial magnetic field is used. The action in the magnetic field is to exert a force on the elec-

trons to keep them going in the correct direction during their transit through the rf section. The magnetic field may be developed by a permanent magnet or by one, or more, electromagnet coils. A permanent magnet is generally used on tubes which are physically small or of medium power rating. Unfortunately, the size and weight of a permanent magnet becomes excessive for long or high power tubes, making it necessary to use electromagnets. In some large tubes several, separate, magnet coils are used; the current in each coil is individually adjustable to optimize the magnetic field shape. The magnetic field is normally terminated as quickly as possible after the catcher cavity so that the beam can spread before it hits the collector. This tends to spread the electron beam interception over a large surface on the collector; this minimizes collector-cooling problems which would result if the beam remained concentrated at the time of interception.

Even with an axial magnetic field some electrons will go "astray" and not remain in the main electron beam. These electrons will be intercepted by the anode or the klystron drift tubes. In high power tubes is it particularly important to minimize the number of these stray electrons because they generate heat when they strike the drift tubes. In high-power klystrons this heating can be a very severe problem because drift tubes are difficult to cool. Temperatures can become high enough to melt the metal in the drift tubes and destroy the tube.



Four-cavity klystron amplifier of the air-cooled permanent-magnet-focused type. This tube delivers 1 kw CW at 5 Gc. Light weight, simple operation, and ability to operate without auxiliary equipment for cooling and focusing make this tube suitable for forward scatter communication and other medium power applications.

The collector is normally insulated from the rf section of large klystron amplifiers to permit separate metering of the electrons intercepted by the drift tubes, and those intercepted by the collector. The electrons intercepted by the rf section are normally referred to as "body current," while those electrons intercepted by the collector are normally referred to as "collector current." Obviously, the sum of body current and collector current is equal to the total current in the electron beam—which is normally referred to as "beam current." Klystron amplifier specifications will quite often place a maximum limit on allowable body current.

The previous discussion (describing the general theory of klystron operation) implied that klystron amplifiers normally have actual metal grid structures across the gaps in the resonant cavities. Many low power klystrons do indeed have wire-mesh grids. However, most high-power klystrons do not have actual grids across the gaps, because such grids would intercept sizable amounts of the electron beam. It is very difficult to cool grid structures, and large beam interception would cause the grids to melt, destroying the tube. Fortunately, by proper design, the klystron can be made to work efficiently without actual grid wires across the gaps. The absence of these grids does not change the operating principles discussed previously, but it does have a secondary effect on the klystron performance. It turns out that, if the electron beam has a very small diameter compared to the size of the drift tubes, the beam does not "couple" strongly to the gaps and therefore it does not react as strongly with the klystron cavity. Therefore, the performance of a klystron amplifier, which does not have gridded gaps, can sometimes be improved by permitting the electron beam to be as large as possible (while keeping the body current down to the maximum specified for the tube). The size of the beam can be somewhat controlled by the magnetic field strength. We therefore find that the klystron performance can sometimes be improved by adjusting the magnetic

field in a way which does not result in the minimum possible body current condition, i.e., by adjusting the field so that the beam shape is somewhat larger than the minimum obtainable. In gridless-gap klystrons therefore, best operation may be obtained with a body current which is not the minimum obtainable; however, body current must be kept within the maximum specified for the tube.

Body current usually increases with rf input level which might be expected since rf causes electron bunches to form. The dense electron concentration in the bunch causes the electrons to repel each other, and the diameter of the bunch may become larger than the diameter of the beam without the bunches. Consequently, some of the electrons in the bunch may be lost to the drift tubes, and the body current may increase.

ASSOCIATED EQUIPMENT

In the preceding sections, we have discussed the basic theory of operation of the klystron amplifier *tube*. Considerable additional equipment is required for a complete amplifier system. First, we will need power supplies to deliver the voltages and currents required for the klystron and for the electromagnets. In high-power systems we will need various types of cooling to get rid of the power supply energy which is not converted into rf output power. We will need various rf circuit components to control and measure the rf input to the klystron tube, and to measure the rf output from the tube. For testing we may need a dummy load to dissipate rf output when it may be inconvenient, or impossible, to radiate. We will need a large collection of meters and protective devices to monitor performance and to protect operating personnel (and the equipment itself) in the event of equipment malfunction or operator error. This associated equipment will be discussed in this section.

Power Supplies

Figure 5 is a simplified diagram showing the power supplies used in a typical klystron amplifier. In most klystron tubes the anode and rf section of the tube are connected together inside the vacuum envelope. These parts are normally called the tube "body," and they are generally operated at ground potential as shown in Figure 5. It is convenient to operate the tube body at ground because the input and output connections (either waveguide or coaxial) are then at ground potential; this makes it easy to connect into the rest of the system. Also, this keeps the cavity tuners at ground potential, eliminating any danger to personnel who are tuning the tube.

The beam power supply, shown in Figure 5, generates the voltage required to accelerate the electrons and form the electron beam. It must also deliver the beam current required for the klystron tube itself. As shown, the positive end of the beam supply operates at (nearly) ground potential, whereas the negative output from the supply is the high-potential point in the system.

The design details for beam power supplies vary widely depending upon the application of the power amplifier. However, in general, they employ fairly conventional circuits. They usually include means of adjusting the ac voltage to the primary of the power transformer, either an auto-transformer (such as a Variac*), an Inductrol**, or perhaps an ac generator whose output is varied by adjusting the dc field control. Beam supplies incorporate a step-up transformer, a rectifier circuit, and an LC filter. Either solid-state, hard-tube, or gaseous diodes are used in the rectifier circuit. Tube rectifiers normally have a lower initial cost; however, they require periodic replacement. Solid-state rectifiers, particularly for high voltage and high current, are usually more expensive initially; however, their reliability is excellent after the initial design and de-bugging.

Filter design is quite conventional; the amount of filtering depends upon the allowable ripple for the system. In some special cases, extremely low ripple and extremely good beam voltage regulation is required. For low- and medium-power systems this can often be achieved by electronic regulation of the dc output voltage. The circuits are, technically, fairly conventional; but they may become quite complicated and expensive for the medium-power systems.

For extremely high-power systems electronic regulation has not proven practical up to this time. For these systems it is normal to obtain the primary power from a motor-

* *Registered trademark of the General Radio Company.*

** *Registered trademark of the General Electric Company.*

generator set. The inertia of the large MG set effectively "smooths out" variations in the incoming line voltage; and the ac output from the generator can be quite easily regulated by a feedback system to the generator field. Brute-force filtering is used to achieve the allowable ripple.

Beam voltage and beam current metering are always provided, as well as beam current overload protection. Some systems have beam over-voltage protection to protect the tube against the possibility of power-supply runaway (rare), and against operator error (more common). Since the beam supply is the source of most of the energy in the system it is almost always turned off when any malfunction occurs in the system; this will be discussed in more detail later.

It is usual to provide a variable voltage beam supply so the tube can be operated at whatever power level is desired (within maximum ratings). It is also desirable to have low beam voltage capability; this is useful when a new tube is installed and initial adjustments are being made. Some systems have a feature which automatically starts the beam voltage at a low value when the supply is first turned on; the voltage then slowly increases until it reaches a pre-set level; and it may regulate to that level for changes in ac line voltage. The voltage automatically runs down to a low level when the supply is turned off.

For high power systems it is normal to have some series resistance between the beam supply and the klystron cathode; this limits the tube current to some finite value in case the tube should arc from cathode to ground. Without some limiting resistance the peak current during an arc could be very high and might destroy the cathode surface; with current limiting resistance a tube can often be "cleaned up" even if it is somewhat gassy or if it arcs on initial turn-on. Most klystron amplifiers include a "getter," and some include a VacIon® vacuum pump. A getter will absorb a limited amount of gas which may accumulate after long storage periods, and therefore may permit a slightly-gassy tube to clean up and be perfectly serviceable (if the tube is not damaged during initial start-up). The VacIon pump operates continuously and will absorb a tremendous amount of gas and may allow a tube to continue in service for its normal life even if it has a small vacuum "leak."

Some high power amplifiers use a "crowbar" system to discharge the beam supply very quickly in the event of an internal klystron arc, or other high-voltage fault condition.

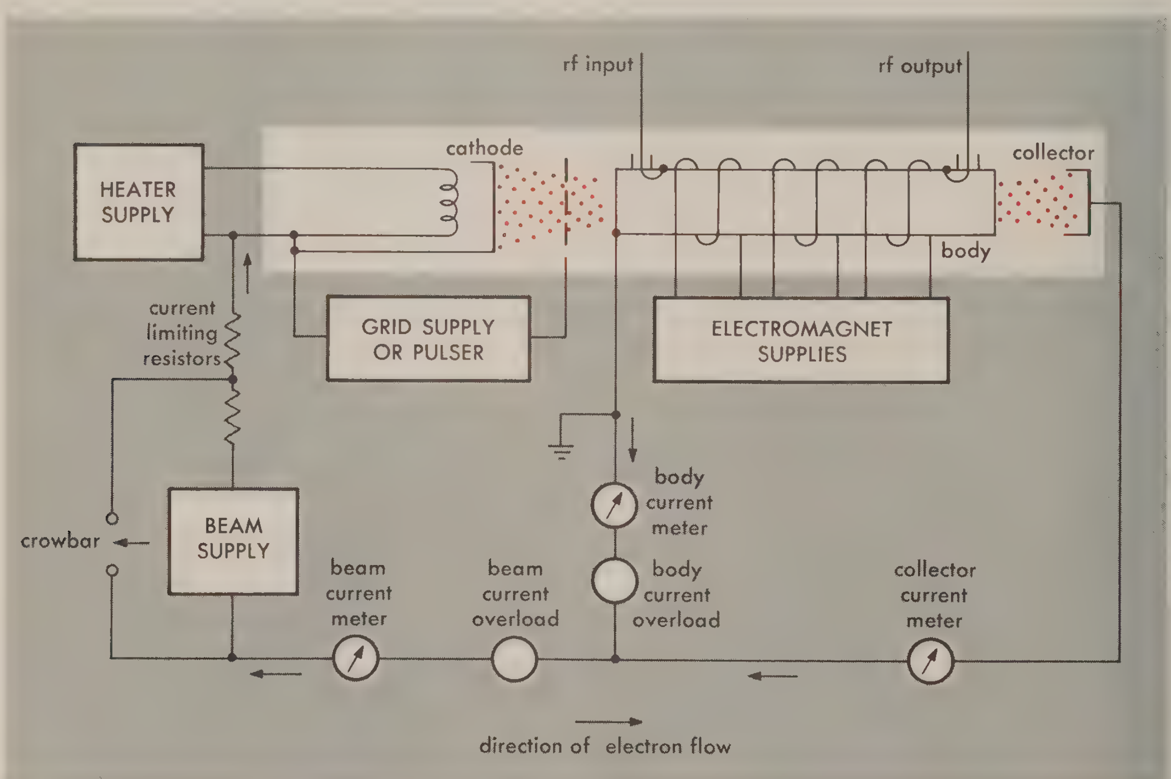
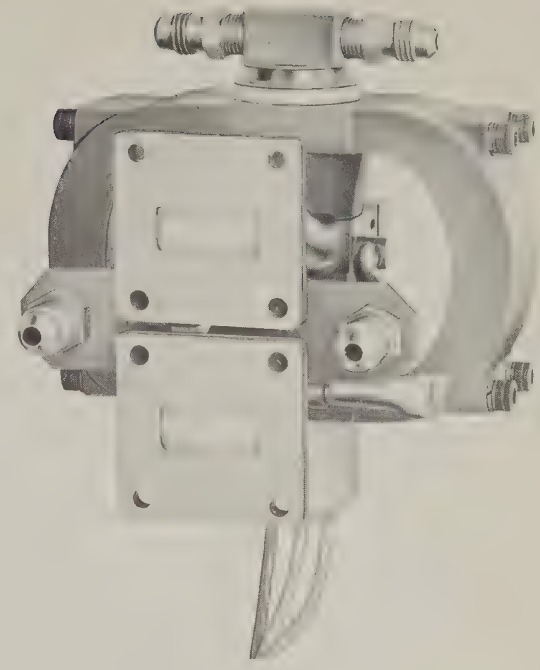


Figure 5. Klystron power supply connections

Most crowbar systems consist of a triggered spark gap connected across the power supply. Circuits are provided which will trigger the gap in case of excessive body current, arcs in the output waveguide (to be discussed later), and (sometimes) loss of magnetic field. When the trigger gap is fired the main spark gap breaks down; this discharges the energy stored in the beam power supply very quickly and prevents damage to the klystron or associated equipment. Crowbars are normally used only on very high voltage, or very high-power systems where the amount of stored energy could cause serious damage. They are normally not used in equipment operating at less than 20-kilowatts average-power; those systems can be adequately protected by simple current-limiting resistors (which are much less complicated and much less expensive than a crowbar system). A crowbar system will normally operate in a few microseconds and therefore will limit the amount of destructive energy delivered to the tube to a very low value. Conversely, it may take several seconds to turn off and discharge a large beam power supply because of the long time required for overload relays and ac contactors and filter capacitors to discharge.

The heater supply furnishes power for the klystron heater, which heats the cathode which, in turn, emits the electrons for the electron beam. Most klystrons have an "indirectly-heated" cathode, i.e., the cathode is heated simply by being in close proximity to the heater windings. A few klystrons have "bombarded" cathodes. In tubes of this type a voltage is applied between the heater and the cathode (with the cathode positive). The heater and cathode then function as a conventional diode. The heater becomes hot enough to emit electrons. These electrons are drawn to the cathode by the "bombarder" voltage. When they strike the cathode they liberate their energy (to the cathode) in the form of heat, just as the plate of a diode is heated by the electrons striking it. Bombarded cathodes have been largely displaced by recently developed "impregnated" cathodes, although a few bombarded-cathode tubes are still in production.

The heater supply is normally a rather simple unit. It may deliver either alternating or direct current. For many applications, an ac supply is adequate; it consists simply of a variable auto-transformer, a stepdown transformer, and appropriate voltage and current metering. In a few systems which require extremely low-noise performance, dc supplies are necessary. The heater supply must be insulated to withstand the full (negative) beam voltage potential. Meters are normally used to show the heater voltage or current or both. Since these meters must operate at a high negative potential they may sometimes give erroneous readings due to the large electrostatic fields present; special care must be taken in the design of metering circuits to prevent these erroneous indications. Heater voltages are normally adjustable to take care of individual tube-to-tube variations and compensate for variation of incoming ac line voltage. A normal klystron heater presents very nearly a short-circuit to the power supply when the heater is cold (first turned on). Therefore it is normal to use some type of current limiting in the heater power supply. Many klystron specifications require that this initial "surge" current be limited to 150 per cent of normal operating current. Protective circuits are often used to turn off the beam power supply if the heater supply fails, since some tubes will be damaged if the beam voltage is "on" while the heater and cathode are



Four-cavity liquid-cooled klystron amplifier with permanent-magnet focusing. This tube, the VA-869, delivers 500-watt pulses at an average power of 200 watts; primarily for airborne pulse doppler navigation systems operating at about 10 Gc.

cooling after a heater supply failure. Some high power klystrons require that the cathode assembly be cooled by an air blower. An airflow protective interlock is normally included to turn off the heater and beam voltage supplies if the klystron blower ceases to operate. The entire "electron gun" section of some very-high-voltage tubes is immersed in oil, for insulation and cooling.

Some klystron amplifiers have a grid (or modulating-anode, which performs the same function) to control the number of electrons in the electron beam. Such grids are often used in pulsed systems to turn the tube either full-on or full-off; a few systems employ grid modulation for transmission of intelligence. In most gridded klystron tubes the grid is never allowed to go positive with respect to the cathode, as this might cause undue grid interception and result in burnout of the grid element. A grid power supply is required in those tubes which have grids. These power supplies and pulsers may take many forms depending upon the system application and will not be discussed in detail. It is important to note, however, that the grid power supply must be insulated for the full beam voltage. Fortunately, most klystron amplifiers which are designed for communication service do not use grids.

The collector of most high power klystrons is insulated from the body of the tube. This allows separate metering and overload protection for the body current and for the collector current—which would be impossible if the collector and the body were connected together internally. In most systems the collector and body operate at very nearly the same potential; any potential difference is normally only the difference in voltage drop across the various metering circuits.

Figure 5 shows three electromagnet coils, apparently wrapped around the body of the klystron. Some klystrons are, indeed, made with the electromagnet coils physically a part of the tube itself. However, in most systems the electromagnet coils are separate from the tube, and the klystron is inserted into the electromagnet structure. In Varian klystrons the electromagnet is designed to physically support and center the klystron tube in the correct position; no physical adjustment of the electromagnet coils is provided—or required for correct operation. Many modern klystron amplifiers have only one electromagnet coil and therefore require only one power supply; others may have as many as six separate coils, requiring one power supply for each coil. Electromagnet power supplies are usually fairly simple. They are dc supplies using conventional rectifying techniques. Voltage variation is normally accomplished with an auto-transformer on the input. The supplies are usually well filtered so that the output current contains relatively small ripple components. Ripple on the electromagnet current may cause the electron beam in the klystron to "wander" slightly, at the ripple frequency; this can cause undesirable amplitude and phase modulation of the rf output signal. Voltage and current metering is normally supplied for each of the electromagnet power supplies. If an electromagnet power supply should fail, the electron beam would almost certainly spread, and the total beam current would be intercepted on a small section of the drift tube. In most cases, this would cause the drift tube to melt and permanently destroy the tube. Therefore klystron amplifier equipment normally has under-current protection in each of the electromagnet coil circuits. When the magnet current falls below a predetermined level the beam supply is turned off to prevent damage to the klystron. Redundant protection is provided by the body-current overload circuits, which also turn off the beam supply in the event of magnet current failure or misadjustment.

Figure 5 shows the method normally used to monitor body current, collector current, and beam current separately; the diagram shows the most frequent arrangement where the klystron body operates at ground potential. In many systems separate monitoring of collector current is not done since the collector current and total beam current are normally almost equal. It is quite unusual, in a relatively high-power klystron amplifier system, to allow the body current to exceed 10 per cent of the beam current, because high body current usually means low efficiency and increases the danger of burning out drift tubes in the klystron. In very-high-power klystrons the body current is often limited to 1 or 2 per cent of the total beam current. Overcurrent protection is almost always supplied for both body current and beam current. If a tube arcs internally, the arc will always occur between cathode and anode. When this occurs the body current immediately becomes excessive, tripping out the body current over-

load relay. If an arc occurs, the beam current is also much higher than normal, and the beam current overload will also trip out. In fact, almost any high-voltage system fault (such as an insulation breakdown from high voltage to ground) will cause excessive current through the body current meter and overload relay. Because of the possibility of extremely high currents flowing under fault conditions the protection of the body current and beam current meters (from burnout) presents a somewhat difficult problem. This problem is normally solved by using very high-current solid-state rectifiers, connected back-to-back, across the meters. In some cases it is necessary to add a small resistance or inductance in series with the meter. Surge capacitors are normally placed across the combination. It is necessary to connect the rectifiers back-to-back because fault conditions often cause oscillating currents to flow through the meters.

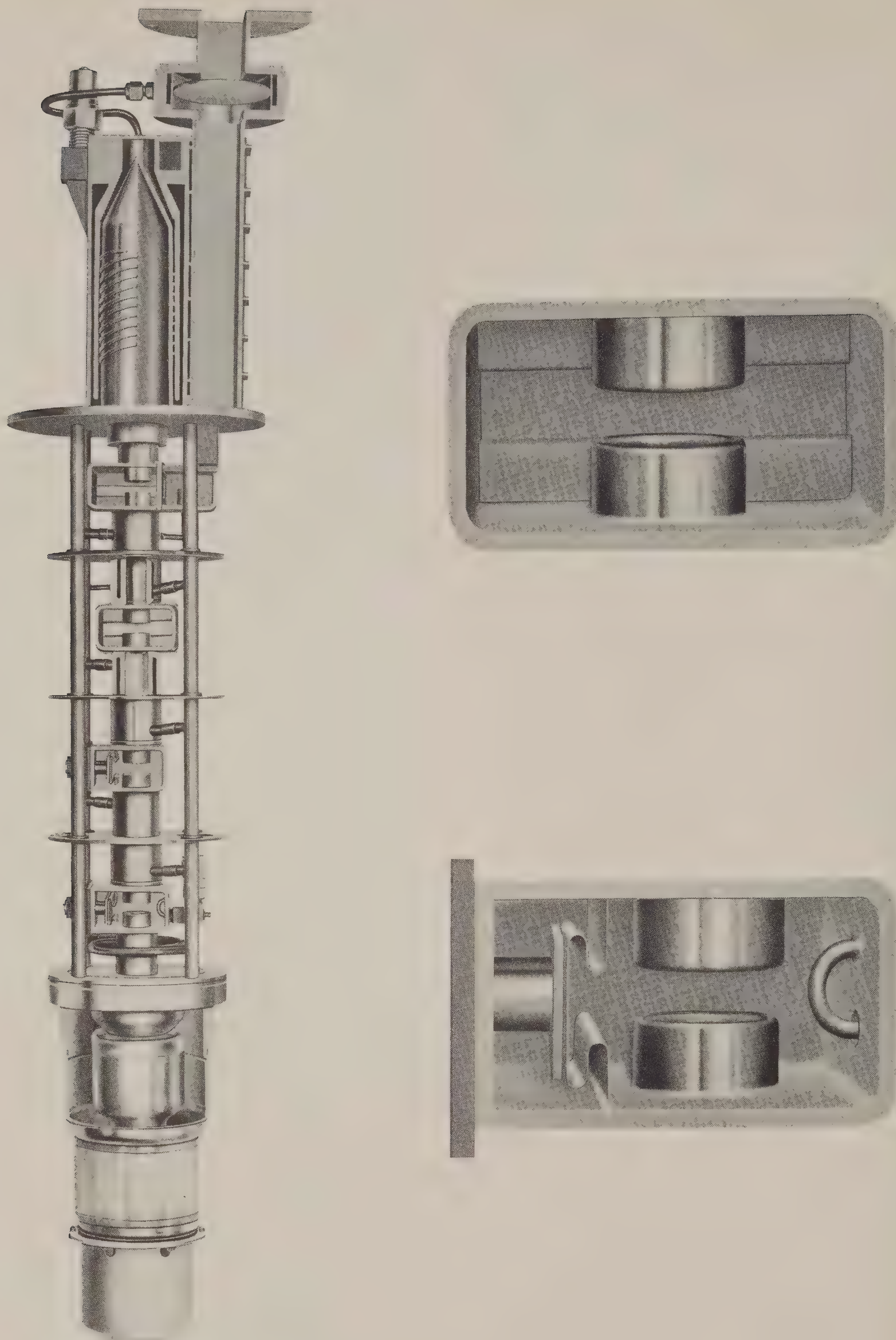
Cooling

Most low power klystron amplifiers are air cooled, while all high power klystron amplifiers are liquid cooled. At the present state-of-the-art, air cooling can be used up to rf output levels of about one kilowatt, CW. However, we find a few special cases where liquid cooling is employed with tubes having a power output as low as 10 watts; these tubes are used in special applications which are beyond the scope of this bulletin.

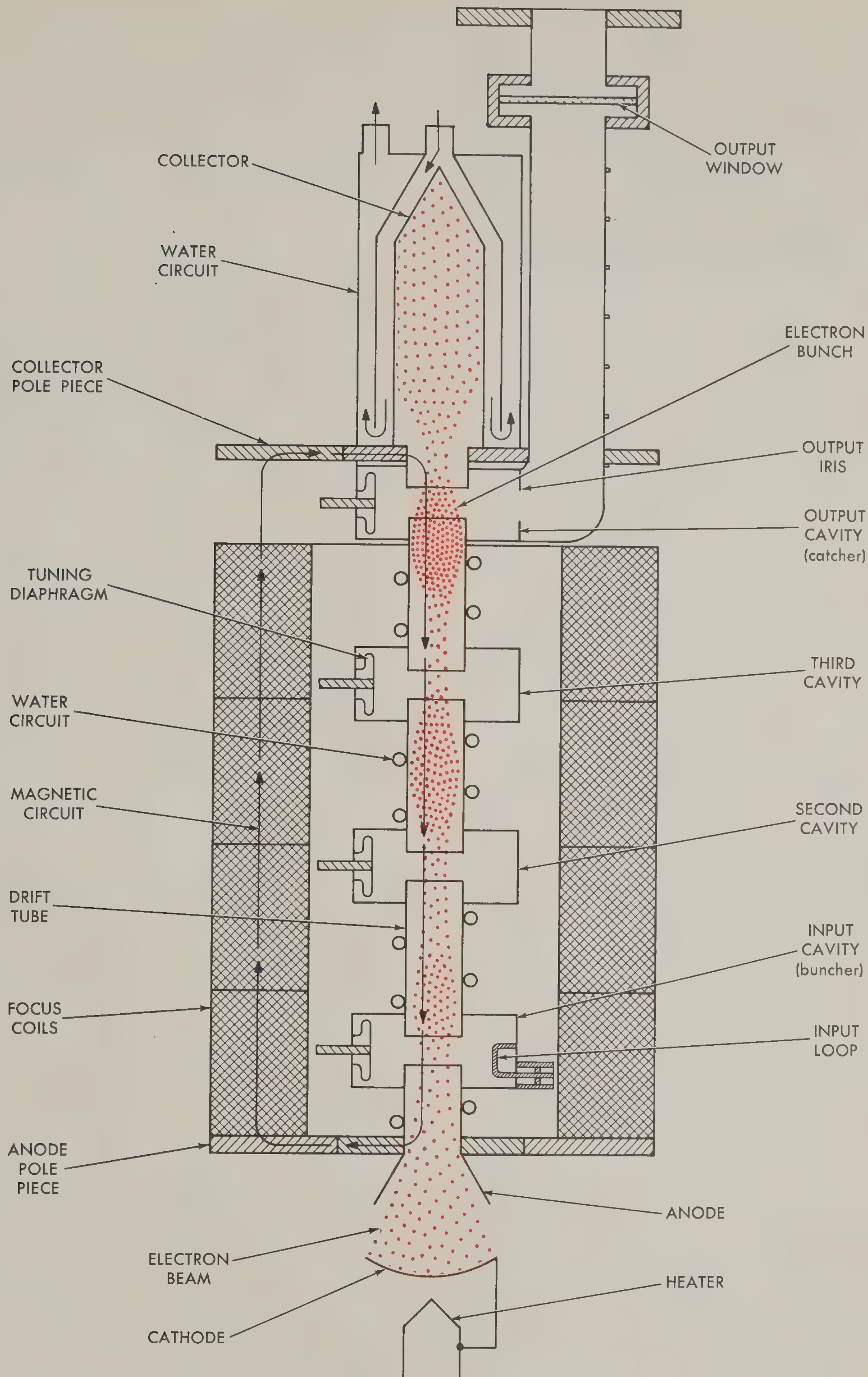
Remember that the main source of power (and therefore heat) in a klystron amplifier package is the beam power supply. The power generated by the beam supply must go somewhere; part of it is converted to rf power; the remainder eventually shows up as heating somewhere in the klystron. The klystron cooling must be adequate to handle the entire beam power because, if no rf output is being generated (either due to low rf input power, or detuning of the klystron tube) then all of the beam power is dissipated in heat somewhere within the tube. As discussed previously, most of the electrons in the beam eventually end up in the collector. When they strike the collector their energy is dissipated and turned into heat. The small fraction of the beam lost to the drift tubes also generates heat. Klystron amplifiers are normally somewhere between 30 and 50 per cent efficient. It is obvious, therefore, that a tube rated at 10 kilowatts output must be designed to dissipate between 20 and 33 kilowatts—depending upon its efficiency. A tube rated at 100 kilowatts must be capable of getting rid of about 250 kilowatts as heat. It is obvious therefore that very advanced cooling techniques are necessary. The power levels involved can melt a hole in the drift tube, or in the collector, in a small fraction of a second if the cooling system fails and adequate protective devices are not provided.

There are other but smaller sources of heat in a klystron amplifier system. The heater must be hot in order to heat the cathode for electron emission. This heat will be conducted and radiated to the exterior surfaces of the electron gun assembly, and must be dissipated. Large tubes require a blower on the electron gun assembly to get rid of this heat. The electromagnet will generate a considerable amount of heat; the power generated by the focus coil power supply is all dissipated in the electromagnet. Large electromagnets are almost always liquid cooled. If the cooling liquid for the electromagnet fails for any reason, the focus coil power supply must be shut off quite soon or the magnet will burn out; the beam voltage must also be removed (preferably before turning off focus coil supply) to protect the tube against excessive body current, as discussed previously.

Earlier in this discussion we described how electron currents oscillate back and forth in the metal walls of the resonant cavities. Although these cavities are made with very high-conductivity metal (usually copper), the metal does present a finite resistance to these oscillating currents; therefore heat will be generated in the cavity walls. The amount of heat generated can be quite sizable in high-power, high-frequency tubes. For instance, consider the case of a 20-kilowatt CW, X-band klystron amplifier. In this tube, approximately 1 kilowatt of heat is generated by the circulating rf currents in the output cavity. Since the cavity is approximately a 1-inch cube, it is apparent that removing this kilowatt of heat is a fairly formidable problem. Cooling the cavity tuners is particularly difficult. Tuners normally incorporate some type of metal bellows arrangement, to permit changing the cavity size and still maintain the vacuum envelope of the tube. Metal bellows are thin structures, normally more lossy than the remainder of the cavity walls; therefore, a large amount of heat is often generated in



High power four-cavity klystron pulse amplifier, cut open to show interior details. The tube's operating frequency is varied by adjusting the diaphragms in the four cavities, two of which are shown in the enlarged views. RF drive is introduced from a coaxial line by the coupling loop in the input (lowest) cavity. Energy given up from the beam in the output (top) cavity leaves the tube through a ceramic window to a waveguide.



Simplified drawing corresponding to photograph on opposite page. Electrons emitted from the cathode at the bottom are formed into bunches as they pass through the tube. Electromagnet surrounding the tube focuses the electron beam and directs it through the cavities and drift tubes to the collector at the top.

the tuner assembly. Removal of this heat is a serious problem in high power tubes, and water cooling is invariably necessary. Another problem associated with cavity heating is not immediately apparent. Remember that the resonant frequency of the cavity depends upon its physical size. The cavities are made of metal which expands as it gets hot; this effect tends to change the resonant frequency of the cavity and to detune the tube. As the tube detunes, the power output will drop; then the rf heating decreases and the tube will tend to come back "in tune." If this problem was not considered in the initial tube design, it would be quite possible to design a tube which would never "settle down"; it would be continually unstable in its operation. This situation indeed exists in some tubes which use "external cavities." These external cavities are cooled by air rather than by liquid, and the cavity tuning is seriously affected by the ambient air temperature. All high-power Varian klystrons are liquid-cooled, including the cavities and the tuners. The cavities are maintained at a stable temperature by controlling the temperature of the cooling liquid, and "thermal-detuning" is no problem.

Drift tube heating is a serious problem in very high-power klystrons, and in medium-power, high-frequency, klystrons. The drift tubes which are inside the vacuum envelope are physically quite small, and it is difficult to remove the heat by conduction to the region outside the vacuum envelope. In some high-power tubes, it is actually necessary to bring the cooling liquid *inside* the vacuum envelope, and around the drift tubes, in order to remove the heat from the drift tubes.

In recent years it has become necessary to cool the waveguide in some high-power, high-frequency systems. RF currents circulate in a waveguide which is carrying power, just as in the cavity walls of the klystron. An X-band waveguide carrying 5 kilowatts CW becomes too hot to touch in normal ambient air. Fortunately, waveguide can be cooled easily by soldering copper tubing along the sides of the waveguide and running cooling liquid through the tubing.

Most klystron amplifiers have a dummy load to dissipate the rf power during adjustment and test (when it may be undesirable to radiate). All high-power dummy loads are cooled, usually by liquid. In many loads the rf energy is dissipated in the cooling liquid itself, since water, oil, and ethylene-glycol (the normal cooling liquids) are quite lossy at microwave frequencies. In other types of dummy loads the rf energy may be dissipated in some sort of a solid, lossy material. Some of these lossy-material loads can be cooled by air blasts (for low- and medium-power applications); higher power versions are liquid cooled.

We have discussed the various sources of heat in a klystron amplifier system, to impress the reader with the fact that an expensive klystron can be destroyed in a matter of seconds if the cooling system fails. A well designed system uses many protective devices to prevent this from happening. The moral is: Check the operation of these protective devices periodically, and *never* "short-circuit" the protective interlocks.

Systems which use blowers for cooling will usually have an air-flow switch. If the blower fails, the switch will open and remove power from the appropriate power supplies. Systems employing liquid cooling normally distribute the liquid into a large number of paths, since the flow requirements are quite dissimilar. A well-designed amplifier system will have a low-flow interlock in each of the various paths. If one of the liquid-cooling circuits becomes plugged, the flow interlock will open and remove power from the system. Liquid-cooling systems also include pressure gauges and pressure switches, temperature gauges and over-temperature switches. Many systems have pressure or flow regulators. Some systems include devices which will sound an alarm before trouble actually occurs; in some cases the situation can be corrected without shutting down the equipment.

In a liquid-cooled system, it is obviously necessary to pump the cooling liquid through the various parts of the tube, and the other equipment which is generating heat. The liquid becomes hotter as it is pumped through these channels, and it is then necessary to get rid of the heat which has gone into the liquid. Some type of heat exchanger is required. Most systems use a liquid-to-air heat exchanger, which consists of a radiator, and a blower which blows air through the radiator—this system is very similar to that on an automobile. The hot liquid passes through the radiator and heats the radiator surface. The air blows across the radiator surface and removes the heat from the radiator. Therefore, the liquid which exits from the radiator

is cooler than the liquid which entered the radiator. In some other systems, primarily those used on shipboard, a liquid-to-liquid heat exchanger may be used. In this device, two liquid cooling paths are involved. One path carries the coolant which is pumped through the klystron amplifier. The other path may carry sea water. Heat is transferred from the klystron cooling liquid to the sea water, and the sea water is dumped back into the ocean. Liquid-to-liquid heat exchangers are smaller than liquid-to-air heat exchangers, and they are also quieter, since no blower is required.

Refer now to Figure 6 which is a fairly detailed diagram of a typical klystron amplifier liquid-cooling system. The right half of Figure 6 shows the method of distributing the cooling liquid to each of the individual channels. The cool liquid enters the "high-pressure manifold" at the top of the drawing. From the high-pressure manifold, the liquid passes through valves which are used to adjust the flow (in each individual channel) to the desired level. The liquid then passes through the component of the system which requires cooling, such as the klystron collector, body, etc. Flow meters are normally incorporated in each of the individual channels to monitor the flow and to make it easy to adjust the flow to the desired level. Liquid flow-switches are placed in each individual channel, so that the appropriate power supplies will be turned off if the flow in that channel falls below the minimum required level. The liquid then goes through shutoff valves into the "low-pressure manifold." Both manifolds are often fitted with temperature gauges and pressure gauges, over-temperature interlocks, and over-pressure interlocks.

In Figure 6 we have shown the waveguide cooling in series with the magnet cooling. Individual system arrangements vary considerably. For instance, in some systems it is possible to put the klystron body cooling in series with the magnet cooling; in other systems the waveguide cooling may be in series with the rf dummy load, etc. The important thing to note is that *each* of the individual channels must have provision for adjustment and measurement of the amount of liquid flowing, and must be provided with low-flow interlock switches for protection. A pressure regulator is often installed somewhere in the system. In Figure 6 it is shown between the high-pressure and low-pressure manifolds.

The middle of Figure 6 shows provisions for cooling the power supply, and any number of other things which may be liquid-cooled in a typical system.

The hot liquid passes from the low-pressure manifold, usually through a filter, and into the heat exchanger. Figure 6 shows a liquid-to-air heat exchanger consisting of a radiator and a blower. After the liquid has been cooled in the heat exchanger, it goes into the "coolant-storage and de-aerator tank."

The de-aerator tank deserves some discussion. Bubbles have a tendency to form in this type of liquid cooling system. Cool liquid will tend to pick up air bubbles if the system is open to the air at any point. As the liquid is heated these bubbles tend to come out of solution. They will tend to collect in "high" parts of the system and may cause difficulty in filling the system in the first place. A fairly small bubble-content in the cooling liquid can seriously diminish the cooling efficiency, and may even cause damage to some of the equipment. Furthermore, air bubbles cause undesirable oxidation of the metal parts of the system. Fortunately, it is quite easy to remove the bubbles. The de-aerator tank is fitted with baffles.

The liquid enters the tank and passes (rather slowly) around and through the baffles in the tank. The bubbles will be released and rise to the surface, rather than remaining in the liquid system. With a de-aerator of this type, it is quite easy to remove bubbles from the system and keep the liquid bubble-free. The air can be bled from the tank, and the tank refilled with liquid if necessary. A low-liquid level switch is normally used in the coolant storage tank. This switch can be connected to ring an alarm which alerts operating personnel to the situation; it may sometimes be connected to shut down the equipment in the event the liquid falls below the safe level.

The liquid passes from the de-aerator tank into a de-ionizer. If free ions are allowed to build up in the cooling liquid, they may eventually cause damage to the collector and body channels in the klystron. The seriousness of this problem varies widely from system to system, and from tube to tube. Some systems require that ions be kept to a very low level. The de-ionizer, normally built with a replaceable cartridge, will remove ions from the liquid and prevent this problem from occurring.

The liquid passes from the de-ionizer into the pump, where it is pumped into the high-pressure manifold. One or more filters are normally included in the cooling system to remove any accumulation of foreign material. In some klystrons the cooling passages are very small and can be plugged easily by dirt or sludge in the cooling system.

Figure 6 shows a nitrogen tank which can be connected to "pressurize" the de-aerator tank. This requires some explanation. Some klystron amplifiers may be located at a considerably higher elevation than the heat exchanger and pump portion of the cooling system; a typical case would be a klystron amplifier located on a large parabolic antenna, with the heat exchanger on the ground. These systems are quite hard to fill because it is difficult to remove the air from the system initially. The problem can be solved with the pressurizing arrangement shown in Figure 6. The storage tank is first filled as full as possible. The drains on the manifolds are opened, and pressure is applied to the storage tank from the nitrogen bottle. The nitrogen pressure forces the liquid out of the tank and up to the manifolds. The air in the lines escapes through the drain valves. When the lines and manifolds are full, the drains are closed. The nitrogen tank is valved off and the storage tank may be filled to the top. The pump can then be started and the remaining air which is trapped in the system will normally be picked up by the coolant and delivered to the de-aerator tank.

Figure 6 shows a bypass line around the heat exchanger radiator, and a temperature-operated bypass valve. This is the system which is often used to control the temperature of the coolant liquid. In the previous discussion, we pointed out that klystron tuning may be changed somewhat by the temperature of the coolant, since this can change the physical size of the cavities. Fortunately, temperature control is done easily by bypassing some of the coolant around the radiator. In systems where the heat exchanger is located fairly close to the klystron tube, the temperature valve may be simply a bi-metal mechanism which senses the temperature of the liquid as it leaves the radiator. If the liquid is too hot, the valve closes partially and causes more of the total liquid to flow through the radiator. Conversely, if the temperature is too cold, the valve readjusts itself to cause more of the liquid to go around the radiator via the bypass line. If the klystron amplifier is a long distance from the radiator, a temperature sensor is normally placed at the high-pressure manifold. This temperature sensor operates the bypass valve. Since the temperature sensor is a long way from the temperature controller, and it takes an appreciable length of time for the liquid to travel this distance, a proportional controller may be necessary to keep the system from "hunting."

Some systems use motor-operated louvers (in the air stream between the blower and the radiator) for temperature control, rather than the bypass arrangement. Either system, of course, can only control the temperature to some point above ambient since the liquid leaving the radiator will always be somewhat hotter than the temperature of the air blowing through the radiator. Most systems are designed to control the liquid to a temperature between 10 and 20°F higher than the maximum-expected ambient temperature at the particular location. It is fairly easy to hold the liquid temperature within $\pm 5°$F. This close temperature control results in very stable klystron tuning.

Some discussion of cooling liquids is appropriate here. Distilled water is the best all-around liquid for cooling klystron amplifiers. Some very-high-power amplifiers specify that only water can be used. Normal tap water usually has a large mineral content, and causes scaling of the klystron cooling surfaces. Scaling reduces heat transfer and may eventually completely close the cooling channels. If this occurs, the tube will be seriously damaged. Unfortunately, water freezes at an inconveniently high temperature. Many low- and medium-power klystrons permit the use of ethylene-glycol and water as the cooling liquid. The cooling efficiency of ethylene-glycol and water is not as good as pure water. Furthermore, ethylene-glycol reacts with certain types of metals and hoses which might be used in the system; therefore, special care must be taken in designing a system which is to use ethylene-glycol. Only non-ferrous metals should be used in a cooling system for a klystron amplifier.

Some very large tubes only permit water to be used for the coolant. This complicates the design of the cooling system, since care must be taken to protect it from freezing. This is no problem if the system is continually operated, but becomes a very serious problem

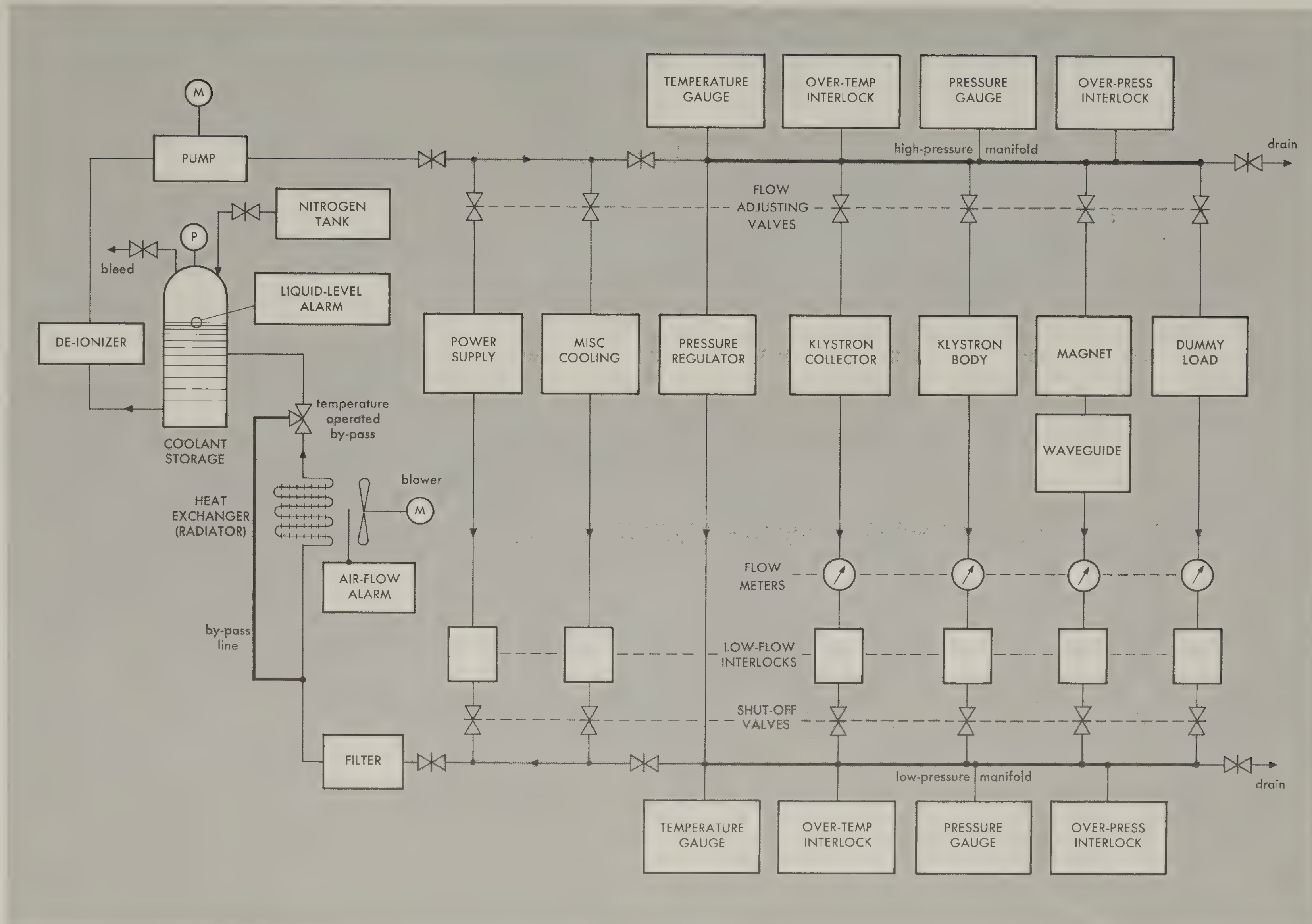


Figure 6. *Typical liquid cooling system for klystron amplifier*

if the system is shut down in cold weather. Some large systems are designed with immersion heaters in the coolant tank. If the klystron is shut down for any reason, these immersion heaters are turned on, and the pump is left running to keep the coolant circulating and prevent freezing.

Additional information on klystron cooling is contained in Varian Application Engineering Bulletin No. 17.

RF Circuits

We have discussed the theory of klystron amplifier operation, power supply requirements, and cooling requirements. Now let us consider what is necessary to get rf into, and out of, the klystron amplifier tube.

Figure 7 shows the rf components typically associated with a klystron power amplifier. We will not consider the rf exciter (or "driver"), since we are only discussing the amplifier portion of a complete transmitter. The rf input signal from the amplifier is derived, of course, from an rf exciter. This signal is shown on the left of Figure 7. The rf input signal normally goes through a ferrite isolator so that a constant rf load impedance is presented to the exciter. The input cavity of a well-designed klystron amplifier normally presents a low VSWR, to the input signal, at the resonant frequency of the cavity; but the VSWR increases very rapidly for frequencies slightly off the resonant frequency of the cavity. It is desirable to isolate these high VSWR's from the exciter; the ferrite isolator accomplishes this function. After the ferrite isolator, the input signal normally is applied to a variable attenuator. The attenuator is used to adjust the input signal level so that the amplifier may operate at saturation, or at lower-than-saturation levels if this should be desired. It may be desirable to monitor the amount of rf input power being applied to the tube. This is normally done with a directional coupler and some sort of rf power monitor. This monitor may be a simple crystal detector and meter, or it may be a thermistor and rf power bridge arrangement.

The input coupler can also be used to help tune the first cavity of the klystron to resonance. Many klystrons have a coarse-tuning indicator which allows them to be set approximately to frequency. However, this is not the case for all tubes, and it may be quite difficult to get them on frequency when they are first put into a system. The first cavity tuning can be done easily by using the input coupler as a "reflected-power" coupler. To do this, put the input monitor on the opposite arm from that shown in Figure 7. When this is done, the monitor will indicate the power which is "reflected" from the first cavity of the tube, back toward the rf exciter. We stated earlier that the cavity presents a low VSWR at its resonant frequency; but if it is not tuned to the frequency of the rf input signal, the input power will be mostly reflected from the first cavity. If we now set up to monitor this reflected power, and then tune the cavity, the reflected power will decrease and go through a null when the cavity is tuned to the frequency of the input signal. This simple procedure allows one to "find" the first cavity and tune it to resonance. After this is done, the rf input monitor is connected to again monitor "forward" input power.

Between the input coupler and the first cavity, the diagram shows a crystal switch. This is a very fast-acting device which will insert between 20 and 30 db attenuation in the rf input line. It is used primarily to remove rf input from the tube quickly in case of arcs in the output waveguide; this will be discussed in more detail later. The crystal switch is normally biased to have low rf attenuation.

This completes the discussion of the components associated with the rf input to the tube.

Let us now consider the rf output components. The first item normally found in the rf output circuit is a waveguide-arc sensor. Waveguide arcs are a troublesome problem in high power CW systems, particularly those at the higher frequencies where waveguide sizes are quite small. Typically, waveguide arcs will occur at power levels above 5 kilowatts at S-band, and above 1 kilowatt at X-band. Although the cause of this arcing is not completely understood, one of the most plausible theories is that ions build up due to thermal ionization from heating of contaminants within the waveguide, or from local area heating at small discontinuities within the waveguide. This ionization builds up in a CW system until the dielectric strength of the gas in the guide is sufficiently reduced to cause a sustained arc to form. Apparently, this build-up of ionization does not occur as readily in pulse systems because the ions have time to disperse during the interval between the

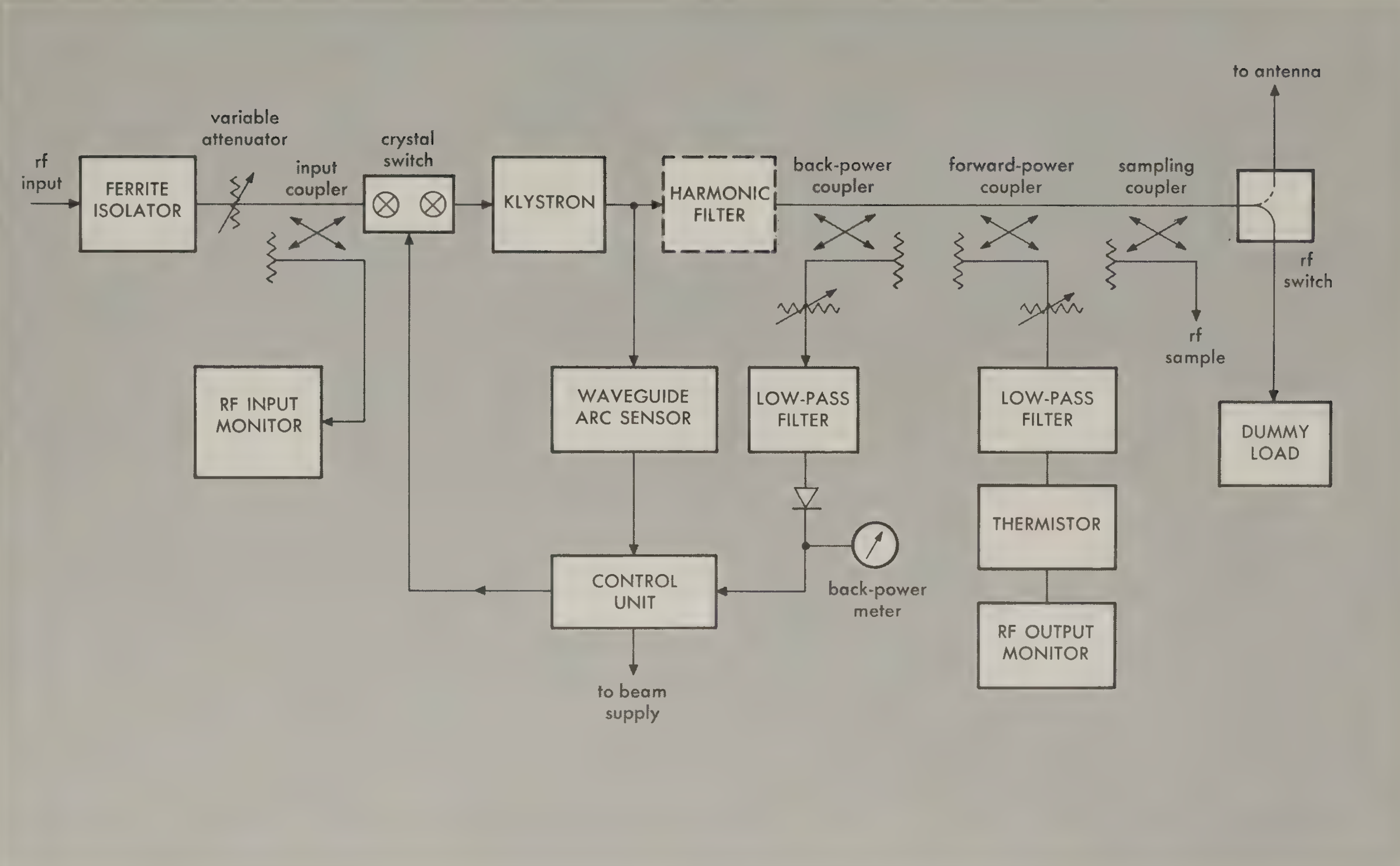


Figure 7. Typical RF circuitry for klystron amplifier

pulses. In any event, once the arc is formed in a CW system, it almost invariably travels toward the source of rf power. If the arc is allowed to reach the output window of the klystron, local heating will occur and the window may be destroyed very quickly. Since the arc presents an effective short-circuit to the waveguide, a very high VSWR exists, and it is quite common to start a secondary arc in other points in the waveguide feedline or at the output window of the klystron.

Experience with very high-power CW amplifiers at X-band indicates that the arc should be quenched in a few microseconds to prevent damaging the tube. This short time precludes removing the rf power by de-energizing the power supplies due to the long time lag of the relays and contactors involved in power supply shutoff. Removing rf drive is the fastest method of quenching the waveguide arc. This removes the rf output power and the arc disappears. Since the arc causes a bright light in the normally dark waveguide interior, a good way to sense the arc is to "look" into the waveguide with some light sensitive device, such as a photo-electric cell or a solar cell. Solar cells have proven superior to photo cells for this service, because they respond more quickly to the presence of light, and because they are less affected by temperature. When an arc occurs, the sensor will develop a voltage, which can be used (with follow-up control circuitry) to change the bias on the crystal switch. This inserts a large amount of attenuation in the rf input to the klystron; the rf output falls 20 or 30 db, and the arc is extinguished. Additional circuits may be used to remove the beam voltage from the klystron if desired.

The next component shown in the rf output circuitry is a "backpower" directional coupler. This coupler is connected to monitor power reflected from a mismatch in the antenna or the dummy load. Klystron amplifier specifications typically require the load VSWR to be below 1.2. Excessive reflected power causes high voltage gradients in the waveguide and excess heating in the tube. It may also tend to detune the last cavity and lower the output. Backpower monitoring is normally done with a directional coupler and some type of rf power meter. As shown in Figure 7, this may be a simple crystal detector and meter, or it may be a thermistor and an rf power bridge. The backpower coupler can be arranged for redundant waveguide-arc protection. If an arc occurs between the coupler and the antenna, a very high VSWR will be present, and the reflected (back) power will rise suddenly. This can be sensed by the crystal detector, which can trigger the control unit of the waveguide arc-detector system. The control unit then changes the bias on the crystal switch, increases its attenuation, and removes the rf output. In this fashion, waveguide arcs occurring far from the light sensor can be detected. Again the beam power supply may be turned off if desired. A variable attenuator is often inserted between the backpower coupler and the detector to permit convenient adjustment to the desired operating level. The backpower meter is often of the type which includes upper-limit contacts. If the backpower slowly increases to an excessive level, these contacts will close and can be used to turn off the beam power supply.

The next component in the rf output circuit is the "forward-power" directional coupler. This coupler monitors the power being delivered to the antenna (or to the dummy load). The power indicating device can, again, be either a simple crystal detector and meter, or it may be a thermistor and an rf power bridge. A variable attenuator is normally included between the coupler and the power monitoring device to permit convenient adjustments. In some systems the power meter has both upper- and lower-limit contacts. These contacts can be arranged to ring alarms if the power output varies excessively.

Many power amplifier systems use a third directional coupler to sample the rf output. Such a sample may be used to monitor noise performance of the equipment, to check distortion in the output signal, etc.

The rf output is normally applied to an antenna. However, a dummy load is very useful for absorbing, and accurately measuring the power being generated. A dummy load is also handy for initial adjustment and tune-up when it may be undesirable to radiate. An rf switch is incorporated in some amplifiers to permit connecting the klystron easily to either the antenna or to the dummy load. This should be done only when the drive has been removed from the tube.

An harmonic filter is sometimes included in the rf output circuit. Depending upon the type of tube and the operating conditions, the output of the klystron may be fairly rich in harmonics. It is not uncommon for the sec-

ond and third harmonics to be only 20 db below the fundamental. In some situations radiation of this harmonic power causes objectionable interference. The harmonic energy can be removed by an harmonic filter in the system. This is simply a low-pass filter which absorbs the harmonic power, while passing the fundamental.

Figure 7 shows low-pass filters in each of the directional coupler output arms. Directional couplers have the "unhappy" characteristic that they usually couple harmonics more strongly than the fundamental. An appreciable amount of harmonic energy present in the rf output may cause erroneous readings in the rf power meters. Simple low-power, low-pass filters remove this harmonic energy from the rf power monitors and prevent this inaccuracy. It is particularly important to have a low-pass filter in the forward power coupler, because the ratio of harmonic energy to fundamental energy is quite dependent upon the way the klystron tube is tuned. If one is watching the forward power meter while tuning the tube, and the harmonics are not suppressed by a filter, it may be difficult to tune the tube correctly.

This discussion has covered the microwave components usually used with a high-power klystron amplifier. The components discussed allow all of the important parameters to be monitored. In addition, some of these components provide features necessary to protect the tube and operating personnel.

TUNING

Tuning a klystron amplifier is very simple, once you understand the principles. Let us consider first the steps to tune the klystron to the synchronous-tuned condition. This is the simplest tuning adjustment. Remember that it results in highest-gain and narrowest-bandwidth operation of the tube. Many klystrons have a dial arrangement which allows adjustment of the cavities to approximately the right frequency before applying power to the tube. However, some tubes have no integral tuning indicators. Most tubes, when delivered are tuned to some frequency, which is indicated by test data accompanying the tube. So, at least, you know where the tube is tuned when you get it, and which direction to go for the desired frequency. The instructions also give the "direction" of tuner rotation to raise, or lower, the cavity frequency. All these things help tune the tube the first time.

Let us consider the most difficult case, a tube with no built-in tuning indicators and no indication of the present tuning. In addition, the driver is fixed-frequency so that you cannot change its frequency to that of the tube; you must tune the tube to the driver. You have installed the tube in the transmitter; the exciter is operating and delivering power; you have the cooling turned on, and voltages are applied to the tube. Everything is working, but you have no power output, because the tube is not tuned to the frequency of the exciter. How do you get power from the tube? It's simple. First, you must adjust the first cavity frequency. When we were discussing Figure 7, we mentioned that you could find the first cavity tuning by reconnecting the "rf input" directional coupler to read the power "reflected" from the tube. This is done by moving the rf input power monitor to the "reflected-power" arm of the coupler. (Don't forget to put the termination on the "forward-power" arm of the coupler.) You are now set up to monitor the power which is reflected from the first cavity of the amplifier. This power will be minimum when the first cavity is tuned to the driver frequency. When you start tuning a tube, it's a good idea to keep some mental notes on how far you've gone, so you can return to the starting point. A simple way to do this is "count turns" as you rotate the tuning tool. So, suppose you begin tuning the first cavity, rotating the tuner in a clockwise direction, and counting turns as you go. Look for a significant "dip" in the rf input monitor which is measuring the reflected power.

You may find some small dips on the way, but look for the major one, which will be the correct tuning point. Most tubes are equipped with tuner stops to prevent damage to the tuner mechanism. Suppose you rotate the tuner clockwise and do not find any major dips in the reflected power all the way to the tuner stop. Then, return to the starting point, counting turns as you go. Then continue counterclockwise (again counting turns from the original position) until you find a significant dip in the reflected power. Minimize the reflected power by tuning. Now you can leave the first cavity alone for a while, since it will be almost on resonance. Reconnect the rf input monitor to read forward power.

Next tune the output cavity. Ignore any

intermediate cavities for the moment. You may still have no measurable reading on the output meter. Increase the rf drive to the highest level you can get from the exciter. Now you are ready to tune the output cavity. Although you may have tuned the first cavity counterclockwise, it does not necessarily follow that the other tuners should be turned the same direction. Refer carefully to Operating Instructions or to markings on the tube itself. Start tuning the output cavity, counting turns as you go. With luck, you will soon bring the output cavity to resonance, and will see an indication on the rf output meter. Maximize this reading by tuning the last cavity of the tube. Once you see *any* reading on the rf output meter, the rest is simple. You know you have the first and last cavities in tune (or almost).

If you have a three-cavity tube, now adjust the middle cavity. Determine the tuning direction from the instructions or tube markings or carefully try one direction and then the other. Simply tune the cavity to maximize the power output reading. However, once you approach a sizable output, it is a good idea to reduce the rf drive to be sure that you do not inadvertently saturate the tube. Tune the middle cavity to maximize the power output reading. Now reduce the drive to a low level, so that the power output meter is far below full power (less than 30 per cent of full-power). Retune the input cavity to resonance; then retune the output cavity to resonance; and then retune the middle cavity to resonance. The tube is now synchronously-tuned. Synchronous-tuning is always done with low rf input power. Now increase the rf drive until the tube saturates (or to whatever power level you may wish to use).

The procedure for a four-cavity tube is very nearly the same. First, tune the input and output cavities to resonance; then the intermediate cavities one at a time. Cavities are often numbered, number 1 being the input cavity and the number 4 the output. For synchronously-tuning a four-cavity tube (after you have some power output), reduce the drive to a low level and tune in the sequence 1-4-3-2; i.e., first tune the input cavity, then the output cavity, then the next-to-the-output cavity, and then the next-to-the-input cavity. The tuning of the fourth cavity is normally quite "broad," whereas the tuning of the first, second, and third cavities is quite "sharp." The reason is that the output cavity is fairly "low-Q" compared to the other cavities.

You have now learned to tune a klystron to the synchronous-tuned condition. This is always the first tuning condition even if you want to stagger-tune the tube later. There are several methods of stagger-tuning, two of which will be discussed briefly. Remember, in Theory of Operation we stated that stagger-tuning could be used to obtain more power than synchronous-tuning. This is done simply by adjusting the third cavity to a higher frequency. The detailed steps are approximately as follows: First, tune the tube synchronously at low rf input; then increase the rf drive until the tube is saturated. Now, leave the drive alone and detune the third cavity in the high-frequency direction. The Operating Instructions for the tube will tell you whether this is clockwise or counterclockwise. As you detune the third cavity, the output will decrease, because more drive is needed for saturation. Continue detuning until the power output has dropped approximately 6 to 10 db. Now increase the rf drive power until the tube again is operating at saturation. You will find that this "new" saturated output is higher than the output obtained with the tube synchronously-tuned. You may be able to "squeeze a little more out" of the tube, but probably not much. You can detune the third cavity still farther and then increase the drive to see if you get more power output than before. The power-output maximum is normally quite broad; you will be able to detune the third cavity considerably either side of this point without making an appreciable change in output. Eventually you may become limited by the amount of power available from the exciter.

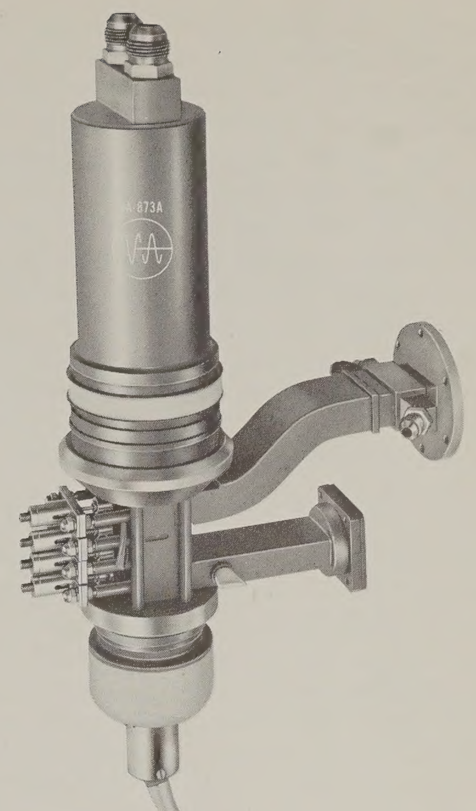
A second type of stagger-tuning should be mentioned. This is stagger-tuning to achieve a desired bandwidth characteristic over the passband. The problem is similar to broadbanding an IF amplifier by stagger-tuning. You will need an rf driver which can be swept in frequency rapidly (electronically-swept), and whose power output is constant during sweeping. You will need to sample the rf output with a crystal detector. Apply the crystal detector output to an oscilloscope so that you can see the passband of the tube. The X-axis of the oscilloscope sweep must be synchronized with the rf input sweep voltage. Again you will start with the synchronous-tuned condition and probably with the tube

operating at saturation. To broad-band the tube, it is usually best to detune the third cavity to the high frequency side, and to detune the second cavity to the low frequency side (assuming a four-cavity klystron). The first and fourth cavity normally are left tuned to the center of the passband. You may wish to adjust the rf input power periodically, as you detune the klystron, to keep the tube operating near saturation. You will find that the bandwidth of the tube is larger when you are operating at saturation than below saturation. The details of the broad-band tuning which you may wish to accomplish are beyond the scope of this note. We have only indicated the equipment which is necessary and the general procedures to be followed.

NOISE IN KLYSTRON AMPLIFIERS

Volumes have been written about noise in microwave systems; obviously, we can only touch the very high points in this discussion. Noise is anything which causes the rf output signal to be different than the rf input signal. We have already mentioned that the output may contain harmonics. This is primarily because the rf output cavity is excited by "bunches" of electrons which come through the output gap once every cycle. These bunches essentially "kick" the output cavity and cause oscillating currents to flow in it. Since the driving force on the output cavity is not continuous, but rather occurs in quick kicks, it is intuitively evident that the output current may not be purely sinusoidal; therefore, it will contain harmonic components. This situation is quite analogous to a class-C triode amplifier in which the plate current flows in bursts, and sets up oscillating currents in the resonant plate circuit. Class-C amplifiers are also rich in harmonics for the same reason. In general, the harmonic output from klystron amplifiers is largest (percentage-wise with respect to the fundamental carrier power) when the tube is operating at saturation, or is being over-driven beyond saturation. Harmonic content decreases (percentage-wise) when the tube is operated below saturation. As discussed previously, harmonics can be reduced in the output by using harmonic filters.

Another source of distortion is nonlinearity of the klystron. If the rf input signal is amplitude-modulated, the rf output may not "perfectly" follow the rf input. This can result in distortion, becoming worse as the tube is driven closer to saturation on the peaks of the rf input signal. In general, klystron amplifiers should not be used to amplify amplitude-modulated signals if the rf output is driven higher than about 0.7 of the saturated level. Between 70 and 100 per cent of saturation, considerable distortion can occur.



Twenty-five years after the invention of the klystron, development culminated in this 50-kilowatt 8-Gc tube for CW service. Water-cooled and focused by electromagnets this tube is used for earth-to-satellite communication, radar astronomy, and missile illumination. These and similar tubes are operated in equipment of the type described in this bulletin.

A klystron amplifier will generate a certain amount of "white noise," just as any other electron tube. White noise occurs primarily because an electron beam is never "perfectly" homogeneous. The number of electrons will vary slightly with time, primarily due to shot noise at the cathode surface; this variation shows up as random noise in the rf output. A certain amount of noise may also be generated by electrons striking the drift tubes. These are the electrons which create the body

current. The body-current interception may be slightly random; this again will perturb the electron beam and cause a small amount of random noise to appear in the output.

You should understand one interesting effect about klystron amplifiers. Intuitively, one would think that the output of an amplifier cannot possibly be "quieter" than the input signal. In certain cases, the klystron amplifier can, indeed, have an output which is quieter than its input. Consider a tube operated at saturation; this is the normal situation when the intelligence is being transmitted by frequency-modulation of the carrier. And suppose that the output of the rf exciter is fairly "noisy" with amplitude-modulation. The klystron amplifier has the desirable property that it will suppress amplitude-modulation of the input signal, if the tube is being operated at saturation. An examination of the output-vs-input curves shown in Figure 4 will explain how this happens. It is obvious that, with the amplifier operating at saturation, rather large changes in the amplitude of the rf input signal will cause no change in the amplitude of the rf output signal. In some systems this effect is very noticeable, and it is not uncommon to find that the AM noise from the exciter can be suppressed by 10 to 20 db, simply by operating the amplifier at saturation.

Additional information on noise characteristics of klystrons is given in Varian Application Engineering Bulletins Nos. 11 and 18. Definitions of AM and FM noise and methods of measurement are discussed. Equations for computation of noise caused by power supply ripple are derived and examples are given for typical conditions.

SUMMARY

This bulletin has attempted to familiarize you with the basic principles of klystron amplifiers and the equipment usually associated with these tubes. Precautionary measures and safety devices have been described in considerable detail in order to explain their importance, and to convince you that "cheating" them for expediency will very likely result in expensive damage to tubes, equipment, or personnel. Tuning procedures described are those used for Varian klystrons but are generally applicable to similar tubes. Too much can not be said in favor of studying Operating Instructions for equipment and tubes thoroughly *before* applying power to your transmitter.

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